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Research on Structural Optimization Design of CNC Machine Tools in the Context of Green Manufacturing

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Abstract: As a pillar industry of the national economy, manufacturing is facing dual challenges of excessive resource consumption and environmental pollution. Against this backdrop, green manufacturing has become an inevitable trend for industrial transformation and upgrading. Metal-cutting machine tools, as the "mother machines" of the industrial manufacturing sector, play a pivotal role in improving energy utilization efficiency and reducing waste emissions through structural optimization design. This paper elaborates on four aspects of structural optimization design in the field of machine tools: structural parameter optimization achieves lightweight machine tool structures by precisely identifying optimal parameter combinations; topology optimization scientifically determines the optimal material distribution scheme during the conceptual design phase; structural bionic optimization draws inspiration from the intricate structures of natural organisms to design bionic structures that are both lightweight and high-performance, encompassing two main approaches: structural morphology bionics and growth mechanism bionics; and multi-method comprehensive structural optimization integrates various optimization techniques, comprehensively considering design constraints and practical conditions to generate lightweight solutions that better align with real-world needs. Research indicates that lightweight design of machine tool structures holds significant potential. By achieving lightweight goals for moving components through structural optimization, material consumption can be effectively reduced, and operational efficiency can be significantly enhanced, marking a critical step toward green manufacturing. Deeply integrating the concept of green manufacturing into traditional mechanical manufacturing is of profound significance for promoting sustainable development in the industry and achieving higher levels of intelligent manufacturing.

1. Introduction

As a pillar industry of the national economy, manufacturing not only creates abundant material wealth for society but also consumes vast amounts of energy and generates substantial solid, liquid, and gaseous waste, causing direct or indirect environmental pollution [1]. With the intensification of global energy shortages and environmental pollution issues, governments worldwide are implementing increasingly stringent energy-saving and environmental regulations. Therefore, reducing resource and energy consumption and lowering environmental pollution have become major issues faced by the manufacturing industry. China is a major manufacturing country, and the contradiction between resource and energy consumption and environmental emissions and the sustainable development of the manufacturing industry is particularly prominent. Energy-saving and environmentally friendly green manufacturing technology has become one of the main directions for the future development of the manufacturing industry. Metal-cutting machine tools, as the mother machines of industry, are core equipment in manufacturing and generally have a service life of more than twenty years. Improving their energy efficiency throughout their lifecycle while reducing waste emissions during processing has become a research hotspot in the machine tool field. The International Organization for Standardization (ISO) has established a series of standards to evaluate the energy utilization efficiency and environmental impact of machine tools [2-4]. To reduce the overall energy consumption of machine tools, in addition to adopting new lubrication and cooling technologies, achieving lightweight structures through structural optimization design—particularly for moving components—is a key means of enhancing overall energy utilization efficiency. Thus, the future direction of manufacturing, characterized by green, efficient, and precise features, inevitably demands the adoption of new technologies for machine tool structural optimization design.

To achieve these goals, Fig.1 presents our integrated optimization framework combining parametric, topological, bionic, and hybrid methods for lightweight, high-performance CNC machine tools.

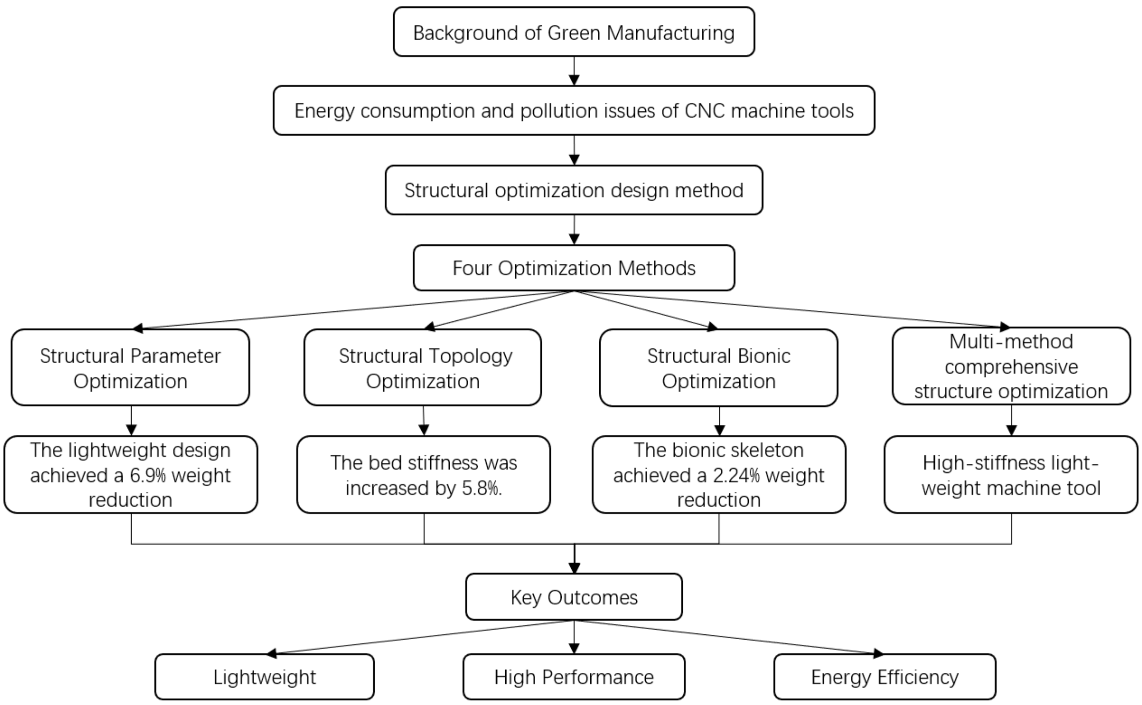

Figure 1: Green structural optimization framework for CNC machine tools.

2. The Application of Structural Optimization Design in CNC Machine Tools

The structure of a machine tool consists of components such as the bed, column, spindle box, and worktable, which bear the cutting loads while maintaining precision. The importance of lightweight design for moving components through structural optimization is evident, while lightweight design for supporting components can achieve uniform load distribution under material-saving conditions, ensuring stress levels are balanced across different parts of the structure. As Schellekens and Rosielle [5] pointed out, lightweight structural configuration design follows the principle of "Design for a high stiffness with designing for a minimum potential energy" which involves using as little material as possible while placing it in the correct shape to maximize functionality per unit weight [6].

Lightweight design for machine tool configurations and structural components has long been a goal in structural optimization. Early machine tool designs relied heavily on designer experience rather than calculations. The structural layout of machine tools largely depended on the machine type and the functional requirements of its components. As early as 1936, closed box-section designs using welding or casting were employed to enhance structural stiffness and reduce resonance [7]. In 1961, some designers proposed that adding inclined ribs inside a closed box could achieve the highest torsional stiffness [8]. This method improved the baseplate design of a column drilling machine, reducing weight by 32%. Empirical design has yielded numerous outstanding design cases. For example, the basic form of the column is designed as a truncated pyramid with a rectangular cross-section, featuring a hollow interior to accommodate counterweights for balancing support and spindle mass. To enhance torsional stiffness and prevent cross-sectional distortion, transverse ribs are incorporated. Sufficient bending stiffness is achieved through the addition of longitudinal ribs. The guide rails are positioned on the side walls, with transverse ribs added to the column wall behind the rails to increase the stiffness of the guide rail section. Building upon this foundation, further force-flow-adapted shape optimization was implemented—the cross-sectional dimensions gradually taper from the base to the top of the column. For specified stiffness requirements, the wall thickness of the plates was further optimized to minimize the overall mass of the column [9]. Beyond columns, empirical designers proposed spindle boxes with circular cross-sections and internal ribs for high torsional stiffness, validated through practical designs.

For complex components, stiffness design based on experience often led to overestimation and excessive structural stiffness, increasing costs [10-11]. With advances in computer technology, virtual prototyping and numerical simulations have mitigated over-design and shortened development cycles [12-13]. As demands for production efficiency, energy utilization, environmental impact, and manufacturing costs grow, systematic structural optimization to reduce mass (inertia) while ensuring stiffness, strength, and damping performance has become a key direction in machine tool design [14].

Researchers from Chemnitz University of Technology, Kroll et al. [15], conducted a systematic study on the lightweight requirements, potential, and effects of major machine tool types, presenting the most suitable candidates for lightweighting and their components through graphical representations. Scholars from Tongji University in China, Zhang Shu et al. [16-17], further elaborated that grinding machines typically lack high-dynamic mechanisms like tool-changing systems or high-acceleration feed axes, with most drive power being consumed by the grinding process itself, rendering lightweighting less effective in energy savings. However, reduced mass can lower transportation costs and operational energy consumption. For lathes, turn-mill centres, and universal milling machines, their motion axes generally do not involve high accelerations, making the energy-saving benefits of lightweighting less pronounced. Nevertheless, if lightweight measures can reduce electrical losses in drive systems—particularly the reactive power consumption during high-dynamic tool-changing processes and workpiece handling systems—it would still be highly beneficial. Five-axis machining centres, high-speed milling centres, and gantry machining centres, primarily used for complex-shaped part processing, frequently undergo multi-axis acceleration/deceleration during coordinated motion; thus, lightweight structures positively impact both dynamic performance and machining efficiency. Laser cutting and waterjet cutting systems often feature long travel distances with accelerations potentially reaching 6G, creating an urgent demand for lightweight solutions. These findings demonstrate the vast potential and promising prospects of lightweight structural design in machine tools [15-17]. Current mainstream lightweight design optimization methodologies for machine tool structures primarily include: structural parameter optimization, topology optimization, multi-constraint integrated structural design approaches, and the emerging bio-inspired optimization design method in recent years.

2.1. Structural Parameter Optimization

Structural parameter optimization aims to identify the optimal structural parameters for detailed component and machine design, serving as one of the common methods to achieve lightweight machine tool structures. As early as 1982, Sun Jing min, a renowned scholar in the field of modern machine tool structural design in China, directly defined the optimal design of machine tool structures as "finding the best values of structural parameters under certain static and dynamic performance constraints as well as dimensional boundary conditions, with the goal of minimizing weight" [18]. He further demonstrated this through mathematical derivations and practical case studies using a spindle as an example [19]. Compared to topology optimization, parameter optimization design is easier to implement and can guide the selection of structural design parameters. Many scholars have incorporated sensitivity analysis methods into parameter optimization. Sensitivity analysis is a method used to study and analyse how changes in system parameters or surrounding conditions affect the state or output of a system (or model). In the context of machine tool structural parameter optimization, sensitivity analysis can be employed to investigate the stability of system performance when structural parameters contain errors or undergo variations. In such cases, sensitivity analysis can be performed by directly deriving characteristic problems or using finite difference methods. Sensitivity analysis can also be used to study the impact of structural parameters on the overall performance of the machine tool, thereby identifying parameters that significantly influence system performance. Here, conclusions often cannot be drawn directly through derivation or difference methods; instead, a mathematical model must be established for analytical solutions, or statistical methods must be applied to discern patterns of variation and draw conclusions. Guo Lei et al. from Tsinghua University [20] used dimensional sensitivity as the optimization parameter, structural component mass as the optimization objective, and stiffness and casting process conditions as constraints to achieve a lightweight design for a machine tool. Their approach ensured no reduction in stiffness while reducing the weight by 312 kg, a decrease of 6.9%, proposing a feasible method for lightweight machine tool design.

With the development of parametric modelling of machine tool geometry, both geometric modelling and finite element analysis can conveniently support design modifications. The advantages of parametric optimization methods are evident, and they have been maturely and widely applied in machine tool configuration design. However, when using parametric optimization methods for machine tool structural optimization currently, the lack of an accurate definition of the mechanical performance of specific machine tool structures makes it impossible to establish reasonable constraint conditions in the optimization mathematical model. As a result, the derived "optimal solution" fails to truly achieve the minimization of structural mass.

2.2. Structural Topology Optimization

Topology Optimization is typically employed during the conceptual design phase to obtain structural configuration sketches by calculating the optimal material distribution relative to structural loads. Common topology optimization methods include the Variable Density Method (VDM), Evolutionary Structural Optimization (ESO), and Level Set Method (LSM). Currently, widely used topology optimization software in machine tool structural design includes OptiStruct, MSC Nastran, ANSYS, and COMSOL, most of which utilize the Variable Density Method at their core [21]. The fundamental concept involves introducing a hypothetical density-variable material, where the relative density of each element serves as the design variable. This approach transforms structural topology optimization into a material distribution optimization problem, which is then solved using either the Optimality Criteria Method or Mathematical Programming Method. Kroll et al. [15] proposed a lightweight design approach for machine tool moving components based on Topology Optimization and welded structures, applying this methodology to the X-frame of a five-axis machining centre. The optimization process accounted for various positions of the Y-slider and corresponding load conditions. The research group led by Ding Xiaohong at the University of Shanghai for Science and Technology [22] implemented a Density-Based Topology Optimization technique combined with a Surrogate Model-based Size Optimization method to develop an optimized design for machine tool beds. Using the spacing and thickness of internal ribs and the spacing of support blocks as design variables, with stiffness and natural frequency as optimization objectives, they achieved a 5.8% improvement in bed stiffness while reducing mass by 4.45%.

Due to the inherent conflict between topology optimization results and conventional manufacturing requirements, the application of topology optimization in machine tool structural design faced significant challenges for an extended period. However, with the advancement of emerging manufacturing technologies such as additive manufacturing, the engineering implementation issues of topology-optimized designs are being progressively resolved. Consequently, topology optimization is expected to find increasingly broader applications in lightweight structural design for machine tools.

2.3. Structural Bionic Optimization

In addition to comprehensive analysis of various constraints, another branch of structural optimization involves learning from nature to design lightweight bionic structures [23]. Bionic structures are mechanical devices created by studying biological organisms' architectures to mimic either whole organisms or their specific parts, achieving similar functionalities through structural resemblance. In recent years, structural bionics has been applied to machine tool structural configuration design, resulting in various structures with enhanced stiffness.

2.3.1. Structural Morphology Bionics

By mimicking biological structures to design mechanical devices, similar functions are achieved through analogous architectures. The core concept involves applying organisms' internal organizational patterns and operational mechanisms to engineering technology, thereby optimizing material and structural performance. Zhao Ling's team at Bei hang University [24] emulated biological skeletal structures and sandwich rods for machine tool column design, achieving a 2.24% mass reduction while increasing specific strength by 21.10%. Building on this, Zhao Ling et al. [25-26] incorporated three distinct bio-inspired concepts: hollow stems, sandwich nodes, and radial roots. They employed fuzzy evaluation methods to determine optimal application scenarios for each approach, ultimately developing a lightweight machine tool worktable and investigating bionic-inspired beam designs. Compared to conventional structures, these designs demonstrated a 3.31% mass reduction with a 23.29% improvement in specific stiffness.

2.3.2. Growth Mechanism Bionics

Structural morphology bionics involves copying and modifying the natural forms of biological structures, while another bionic optimization approach derives lightweight structures by learning the growth mechanisms of natural biological systems based on load-bearing conditions and design objectives. A representative example of this method is the adaptive growth algorithm proposed by Ding Xiaohong et al. [27-29] from the University of Shanghai for Science and Technology. This algorithm investigates the morphological formation mechanisms of various branching systems in nature (e.g., plant root systems) to simulate the growth of reinforcing ribs in machine tool structures. Under specific load boundary conditions, these ribs grow along directions that optimize certain structural performance metrics (e.g., minimizing strain energy), ultimately yielding rational rib configurations [30-38]. Ding Xiaohong et al. [36-38] applied the adaptive growth method to the lightweight design of a vertical machining centre, establishing mathematical optimization models based on actual load conditions to derive optimized structural configurations for components such as the spindle box, column, and bed. Taking the spindle box design as an example, the process begins with creating a design model reflecting real-world conditions—a cantilever structure with a cuboid design area and loads applied along the spindle axis. The design area is then discretized into finite elements to form a base structure for rib design, with nodes at load and support locations serving as initial growth points for rib development. Subsequent finite element analysis and sensitivity calculations guide rib growth along directions maximizing structural stiffness. When a rib reaches a bifurcation threshold, its endpoints become new growth points, enabling connected ribs to grow further. Conversely, if a rib degrades below a certain value, the growth capability of connected ribs is terminated. The final design yields a spindle box with an internal cross-rib structure. Similarly, applying this method to the bed structure results in thicker ribs distributed at load-bearing and constraint points, interconnected by cross-ribs, with two concentric rib rings formed at the mid-section to directly resist deformation. Through morphological and growth-mechanism bionics, biomimetic design has achieved notable research progress in lightweight machine tool structures. Particularly, growth mechanism-based bionic design has emerged as a distinctive and internationally influential scientific direction.

2.4. Multi-method comprehensive structure optimization

In practical design research, designers comprehensively consider design constraints and real-world conditions by integrating empirical design, topology optimization, and parametric optimization—or by unifying structural design with electromechanical system design—or by conducting configuration synthesis under multiple constraints to generate more suitable lightweight solutions. A collaborative study by Stöpplera from Siemens AG (Germany) and Douglasb from Liverpool John Moores University (UK) [39] performed electromechanical coupling analysis on a gantry machine tool driven by linear motors, followed by adaptive structural optimization that reduced weight by removing partial mesh-like reinforcing ribs from moving components. Since the early 21st century, multi-method integrated design has been applied to various machine tool designs in China. For instance, the VTC8080 vertical lathe developed by Shenyang Machine Tool Group incorporated finite element static and dynamic simulation analysis on top of empirical design to optimize the bed structure for lightweight performance. Experimental validation confirmed its high rigidity and precision [40]. Yang Chang qing from Tianjin University of Technology [41] conducted structural optimization for a large machining centre based on multi-objective optimization. Meanwhile, Prof. Huang Tian’s team at Tianjin University [42] specifically investigated mechanisms that ensure machining accuracy and dynamic response. By comprehensively evaluating practical requirements such as reconfigurability, motion capability, and rational component design, they proposed a criterion for selecting suitable structures from numerous candidates: "An appropriate configuration must permit (via joint type and arrangement) all lower moving components to achieve shapes with high bending and/or torsional stiffness-to-mass ratios." Subsequently, integrating all joints connecting the base link and frame into a compact part enabled a lightweight, cost-effective, and flexible design—particularly suited for configuring parallel machine tools. As the scope of considerations expands, theoretical analysis and computational methods in lightweight machine tool structural and configuration design increasingly incorporate multidisciplinary knowledge, synthesizing diverse approaches to yield distinctive research outcomes.

3. Conclusions

Machine tools, as mother machines and long-lifecycle products, primarily consume energy during production and operation. The design, manufacturing, and management technologies for high-efficiency green machine tools have become a key focus in academia and industry worldwide. Achieving lightweight moving components through structural optimization design not only reduces material consumption but also enhances operational efficiency, representing a critical step toward green manufacturing. Furthermore, in response to the demands of green manufacturing for CNC machine tool structural optimization, this study systematically elaborates on various advanced optimization methods, including structural parameter optimization, structural topology optimization, structural bionic optimization, and multi-method integrated structural optimization. Applying green manufacturing principles to traditional mechanical manufacturing can pave the way for the industry's future, fostering sustainable development and enabling higher-level intelligent manufacturing.

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